PROGRAMMABLE OADM WITH CHROMATIC DISPERSION, DISPERSION SLOPE AND AMPLITUDE RIPPLE COMPENSATION, AND METHOD

Field of the Invention

The invention relates to the field of optical networks. More specifically the invention pertains to optical add/drop multiplexing.

Background of the Invention

Optical add/drop multiplexers (OADMs) are widely used in optical networks. OADMs can be used to provide local termination of traffic and optical cross-connect of multiple optical systems. The main problem in cross-connecting long-haul optical systems include coherent cross-talk (or multi-path interference (MPI)), amplitude equalization and chromatic dispersion. These issues become increasingly problematic in high bit rate applications. Multiple cascaded three-port filters are commonplace, but filter isolation is not absolute and therefore they introduce MPI. The MPI is introduced through a "reflective" express path on which the non-add/drop traffic is routed. Tunable filters are sometimes used but are, in general, unable to be reconfigured without affecting some other traffic on the line other than that being switched.

Summary of the Invention

A programmable optical add/drop multiplexer (OADM) implements an add/drop function of optical signals from a number of cross-connected optical systems while treating issues of coherent cross-talk (or multi-path interference (MPI)), chromatic dispersion, slope of dispersion and amplitude equalization. Input WDM (wavelength division multiplexed) optical signals from a number of optical systems are each de-multiplexed into a number of optical path signals that are

routed through optical switches and then multiplexed into a number of output WDM optical signals. Problems with coherent cross-talk in optical path signals (or equivalently, MPI) are eliminated by introducing equivalent optical path lengths between paths through which the optical path signals propagate and by introducing dead-bands between consecutive optical path signals. Chromatic dispersion, slope of dispersion and amplitude equalization compensation is performed such that at the optical switches respective ones of the optical path signals have a common value of chromatic dispersion, slope of dispersion and power. Chromatic dispersion, slope of dispersion and amplitude equalization compensation is also performed for each one of the output WDM optical signals such that the chromatic dispersion, slope of dispersion and power are set to respective target values satisfying transmission requirements of a respective optical system. In addition, the target values are independent of which optical path signals are being added and dropped.

In accordance with one broad aspect of the invention, the invention provides a method of implementing programmable optical add/drop multiplexing. In the method, for each one of N optical systems, a respective input WDM optical signal is de-multiplexed into a plurality of optical path signals each having at least one channel. An add/drop function is then performed on selected ones of the optical path signals and through paths are established for remaining ones of the optical path signals. In the method, for each one of the N optical systems, a plurality of optical path signals are multiplexed into an output WDM optical signal. Furthermore, at least one of chromatic dispersion compensation, slope of dispersion compensation and amplitude compensation is performed. The chromatic dispersion compensation results in, for each one of the N optical systems, the chromatic dispersion of a respective

one of the output WDM optical signals being independent of the add/drop function and corresponding to a target value. The slope of dispersion results in, for each one of the N optical systems, the slope of dispersion of a respective one of the output WDM optical signals being independent of the add/drop function and corresponding to a target value. The amplitude compensation results in, for each one of the N optical systems, the amplitude of a respective one of the output WDM optical signals being independent of the add/drop function and corresponding to a target value.

Another broad aspect of the invention provides a method of implementing programmable optical add/drop multiplexing of N input WDM optical signals in an optical system. In the method, one or more dead-bands are introduced in each one of the N input WDM optical signals. Each one of the N input WDM optical signals is de-multiplexed into a plurality of optical path signals each comprising at least one channel. Furthermore, one or more of the dead-bands are between two or more of the plurality of optical path signals. An add/drop function is performed on selected ones of the optical path signals wherein the selected ones of the optical path signals and through paths are established for remaining ones of the optical path signals. After having routed the optical path signals using the add/drop function and the through paths respective ones of the optical path signals are multiplexed into N output WDM optical signals.

Another broad aspect of the invention provides a method of implementing programmable optical add/drop multiplexing. The method includes de-multiplexing, for each one of N optical systems, a respective input WDM optical signal. The respective input WDM optical signals may be fully de-multiplexed into a plurality of optical path signals each

having one channel or partially de-multiplexed into a plurality of optical path signals with at least one of the optical path signals having a plurality of channels. The method includes performing an add/drop function of selected ones of the optical path signals and establish through paths of remaining ones of the optical path signals. The method includes multiplexing, for each one of the N optical systems, a plurality of optical path signals into an output WDM optical signal. The method also includes establishing two or more paths of approximately equal optical path lengths between the de-multiplexing and the multiplexing.

The paths of approximately equal optical path lengths may be established by providing equivalent functional elements in the paths of approximately equal optical path lengths. Furthermore, express paths may be established in through paths where optical path signal are not added and dropped. The method may be applied to optical systems in which input WDM optical signals have dead-bands such that when the input WDM optical signals are de-multiplexed the dead bands may be included between concurrent optical path signals of the N optical systems. This may result in mitigation of filtering penalties in de-multiplexing the input WDM optical signals and a reduction of effects of cross-talk between the concurrent optical path signals.

The method may include performing chromatic dispersion compensation. The process of chromatic dispersion compensation may result in each one of the output WDM optical signals of the N optical systems having a chromatic dispersion set to a target value which is suitable for transmission requirements of a respective one of the N optical systems. In addition, the chromatic dispersion may be independent of the optical path signals being added and dropped.

In some embodiments, the chromatic dispersion compensation may include performing preliminary chromatic dispersion compensation and slope of dispersion compensation, for each one of the input WDM optical signals of the N optical systems. This may be done such that the input WDM optical signals are set to common values of chromatic dispersion and slope of dispersion, respectively. Output chromatic dispersion compensation and slope of dispersion compensation of one or more of the output WDM optical signals of the N optical systems may also be performed. In this case, for the one or more of the output WDM optical signals of N optical systems, the chromatic dispersion and the slope of dispersion may be set to target values of chromatic dispersion and slope of dispersion, respectively. These target values may be suitable for transmission requirements of a respective one of the N optical systems. In some embodiments, secondary chromatic dispersion and slope of dispersion compensation may be performed for at least one optical path signal of each one of at least N-1 optical systems of the N optical systems. This may be done such that respective optical path signals of the at least N-1 optical systems may be set to have common values of chromatic dispersion and slope of dispersion, respectively. More particularly, optical path signals at a particular switch may have common values of chromatic dispersion and slope of dispersion. In other embodiments, secondary chromatic dispersion and slope of dispersion compensation may be performed for at least one optical path signal of each one of the input WDM optical signals of the N optical systems. This may be done so that the chromatic dispersions and slopes of dispersion of at least one optical path signal of each one of the input WDM optical signals may be set to common values of chromatic dispersion and slope of dispersion, respectively.

In some embodiments, the method may include performing amplitude compensation. This may be done so that the power of the output WDM optical signals corresponds to target values that may be suitable for transmission requirements of a respective one of the N optical systems. Furthermore the power may be independent of the optical path signals being added and dropped. The amplitude compensation may include performing amplification of each one of the input WDM optical signals of the N optical systems such that the power of each one of the input WDM optical signals of the N optical systems may be set to a common value. The amplitude compensation may also include performing amplification of each one of the output WDM optical signals of the N optical systems. This may be done so that the powers of the output WDM optical signals may be set to target values which are suitable for transmission requirements of respective ones of the N optical systems. Finally, the amplitude compensation may include performing amplitude compensation through amplification and/or attenuation of the optical path signals of the N optical systems such that, for respective ones of the optical path signals of the N optical systems, the power may be set to a specific common value.

Another broad aspect of the invention provides a programmable optical add/drop multiplexer (OADM). The programmable OADM includes two or more OADM elements. Each one of the OADM elements has a de-multiplexer (DeMUX) and a multiplexer (MUX) connected through a plurality of paths. Each one of the DeMUXs is used to de-multiplex an input WDM optical signal into a plurality of optical path signals and each one of the optical path signals propagates through a respective one of the paths. Each one of the MUXs is used to multiplex a plurality of optical path signals into an output WDM optical signal. A plurality of switches are each connected to

respective ones of the paths of the two or more OADM elements. The switches are used to perform an add/drop function of selected ones of the optical path signals of the two or more OADM elements and to establish through paths of remaining ones of the optical path signals of the two or more OADM elements. The programmable has at least one of a plurality of dispersion and slope of dispersion compensation modules (DSCMs), a plurality of optical amplifiers and a plurality of variable gain control elements (VGCEs). The DSCMs are used to perform at least one of dispersion compensation and slope of dispersion compensation in a manner that, for each one of the two or more OADM elements, the dispersion and slope of dispersion, respectively, of the output WDM optical signal is independent of the state of the switches. Furthermore, the optical amplifiers and the VGCEs are used to perform amplitude compensation in a manner that, for each one of the two or more OADM elements, the amplitude of the output WDM optical signal is independent of the state of the switches.

Another broad aspect of the invention provides an optical system. Within the optical system there is at least one transmitter that is used to generate optical signals each comprising one or more channel wherein channel frequencies at which the optical signals are generated are limited to provide dead-bands. The optical system also has a programmable OADM. The programmable OADM has two or more OADM elements. Each one of the OADM elements has a DeMUX and a MUX connected through a plurality of paths, wherein the DeMUX is adapted to de-multiplex an input WDM optical signal into a plurality of optical path signals. The input WDM optical signal carries dead-bands and when the input WDM optical signal is de-multiplexed least one of the dead-bands within input WDM optical signal between at least two of the optical path signals. Each one of the optical path signals propagates

through a respective one of the paths. Furthermore, each one of the MUXs is adapted to multiplex a plurality of optical path signals into an output WDM optical signal. A plurality of switches are each connected to respective ones of the paths of the two or more OADM elements. The switches are used to perform add/drop function of selected ones of the optical path signals of the two or more OADM elements and to establish through paths of remaining ones of the optical path signals of the two or more OADM elements.

Another broad aspect of the invention provides a programmable OADM that has two or more OADM elements. Each one of the OADM elements has a DeMUX and a MUX. They are connected through a number of paths such that the DeMUX de-multiplexes an input WDM optical signal into a plurality of optical path signals each propagating through a respective one of the paths. Each one of the MUXs multiplexes a plurality of optical path signals into an output WDM optical signal. The programmable OADM includes a plurality of switches each connected to respective ones of the paths of the two or more OADM elements. The switches perform an add/drop function of selected ones of the optical path signals of the two optical systems and establish through paths of remaining ones of the optical path signals of the two optical systems. The programmable OADM also has optical path length means for reducing effects of coherent cross-talk between the optical path signals.

The programmable OADM may also have any one or more of chromatic dispersion means, slope of dispersion means and amplitude compensation means to assure that the chromatic dispersion, slope of dispersion, and amplitude, respectively, of the output WDM optical signals are independent of the state of the switches and set to respective target values.

To summarize, the programmable OADM implements add/drop function of optical signals from a number of cross-connected optical systems while concurrently treating issues of coherent cross-talk, chromatic dispersion, slope of dispersion and amplitude equalization.

Brief Description of the Drawings

Preferred embodiments of the invention will now be described with reference to the attached drawings in which:

Figure 1 is a block diagram of a programmable optical add/drop multiplexer (OADM), provided by an embodiment of the invention;

Figure 2A is a list describing one way an input WDM (wavelength division multiplexed) optical signal is partially de-multiplexed into a number of partially de-multiplexed optical path signals; and

Figure 2B is a list describing another way an input WDM optical signal is partially de-multiplexed into a number of partially de-multiplexed optical path signals.

Detailed Description of the Preferred Embodiments

Referring to Figure 1, shown is a block diagram of a programmable optical add/drop multiplexer (OADM) **10**, provided by an embodiment of the invention. The programmable OADM **10** of Figure 1 is an arrangement of optical amplifiers, dispersion and slope compensation modules (DSCMs), multiplexers (MUX), de-multiplexers (DeMUX), variable gain control elements (which can be amplifiers, attenuators or both) and optical switches. The preferred embodiment of Figure 1 is used to perform optical add/drop multiplexing of WDM (wavelength division multiplexed) optical signals between two optical systems.

An input optical amplifier **11** is connected to an input **1** of the programmable OADM **10** and to a primary DSCM **21**. Preferably, the primary DSCM **21** is a broadband DSCM. The primary DSCM **21** is connected to an input **131** of a DeMUX **31**. The DeMUX **31** and a MUX **33** form a MUX/DeMUX pair connected through eight paths. In a preferred embodiment of the invention, the DeMUX **31** and the MUX **33** are both optical wavelength division multiplexing filters. Each path includes a respective one of eight secondary DSCMs **81, 82, 83, 84, 85, 86, 87** and **88**, a respective one of eight variable gain control elements (VGCEs) **101, 102, 103, 104, 105, 106, 107** and **108**, and a respective one of eight optical switches **121, 122, 123, 124, 125, 126, 127** and **128**. In a preferred embodiment of the invention, the secondary DSCMs **81** to **88** are narrow-band DSCMs and the optical switches **121** to **128** are 2x2 optical switches. An output **133** of the MUX **33** is connected to an output DSCM **23** and the output DSCM **23** is connected to an output optical amplifier **13**. The output optical amplifier **13** is connected to an output **3** of the programmable OADM **10**. The input **1**, the input optical amplifier **11**, the primary DSCM **21**, the DeMUX **31**, the secondary DSCMs **81** to **88**, the VGCEs **101** to **108**, the MUX **33**, the output DSCM **23**, the output optical amplifier **13** and the output **3** form an OADM element **500**.

An input optical amplifier **12** is connected to an input **2** of the programmable OADM **10** and to a primary DSCM **22**. Preferably, the primary DSCM **22** is a broadband DSCM. The primary DSCM **22** is connected to an input **132** of a DeMUX **32**. The DeMUX **32** and a MUX **34** form a MUX/DeMUX pair connected through eight paths. In a preferred embodiment of the invention, the DeMUX **32** and the MUX **34** are both optical wavelength division multiplexing filters. Each path includes a respective one of eight secondary DSCMs **91, 92, 93, 94, 95, 96, 97** and **98**, a respective one of eight variable gain control elements (VGCEs)

111, 112, 113, 114, 115, 116, 117 and **118**, and a respective one of the optical switches **121, 122, 123, 124, 125, 126, 127** and **128.** In a preferred embodiment of the invention, the secondary DSCMs **91** to **98** are narrow-band DSCMs. An output **134** of the MUX **34** is connected to an output DSCM **24** and the output DSCM **24** is connected to an output optical amplifier **14.** The output optical amplifier **14** is connected to an output **4** of the programmable OADM **10.** The input **2,** the input optical amplifier **12,** the primary DSCM **22,** the DeMUX **32,** the secondary DSCMs **91** to **98,** the VGCEs **111** to **118,** the MUX **34,** the output DSCM **24,** the output optical amplifier **14** and the output **4** form an OADM element **600.**

The programmable OADM **10** features add/drop functions for adding and dropping channels between two optical systems. In adding and dropping channels between the two optical systems, a number of problems such as coherent cross-talk (or multi-path interference (MPI)), chromatic dispersion and amplitude equalization must be treated; 1) Coherent cross-talk may occur during channel filtering processes at the DeMUXs **31, 32** and the MUXs **33, 34.** More particularly, an input WDM optical signal which is de-multiplexed by one of the DeMUXs **31, 32** results in paths signal propagating through respective paths to one of the MUXs **33, 34.** In de-multiplexing, frequency leakage from one of the respective paths into other ones of the respective paths may occur causing coherent cross-talk at the MUXs **33, 34** where optical path signals are being multiplexed into output WDM optical signals. When the respective paths have different optical path lengths the coherent cross-talk due to the frequency leakage may compromise the integrity of the output WDM optical signals. 2) Chromatic dispersion of an optical signal depends on the length over which the optical signal has traveled. Therefore, for example, two input WDM optical signals at inputs 1 and 2 may have different chromatic

dispersions. The programmable OADM **10** must therefore compensate for mismatches in chromatic dispersion of input WDM optical signals when cross-connecting optical systems. 3) In addition, chromatic dispersion is wavelength dependent, resulting in a slope of dispersion. The slope of dispersion is specific to the type of optical fiber through which an WDM optical signal propagates. The programmable OADM **10** must therefore also compensate for any mismatches in slope of dispersion when cross-connecting optical systems with different optical fibers through which respective WDM optical signals propagate. 4) Finally, WDM optical signals from different optical systems may be at different amplification stages at the point where the cross-connections occur. The programmable OADM **10** must therefore compensate for mismatches in the power spectrum and perform amplitude equalization. The programmable OADM **10** implements add/drop functions while treating the issues of coherent cross-talk, chromatic dispersion, slope of dispersion and amplitude equalization.

An input WDM optical signal from a first optical system is input at the input **1** of the programmable OADM **10** and propagates to the input optical amplifier **11** where it is amplified. The input WDM optical signal from the first optical system then propagates to the primary DSCM **21**. The primary DSCM **21** performs preliminary chromatic dispersion and slope of dispersion compensation of the input WDM optical signal from the first optical system. The input WDM optical signal from the first optical system then propagates to the DeMUX **31** where it is de-multiplexed into eight optical path signals from the first optical system such that each one of the eight optical path signals from the first optical system includes four channels. In a preferred embodiment of the invention, an input WDM optical signal is partially de-multiplexed into a number of optical path signals meaning that at least one of the optical

path signals is a WDM optical path signal having more than one channel associated with it. In another embodiment of the invention, an input WDM optical signal is fully de-multiplexed into a number of single channel optical path signals. Referring back to Figure 1, each one of the eight optical path signals propagates to a respective one of the secondary DSCMs **81** to **88**. Each one of the secondary DSCMs **81** to **88** performs secondary chromatic dispersion and slope of dispersion compensation over its respective optical path signal. Each one of the eight optical path signals from the first optical system then propagates to a respective one of the VGCEs **101** to **108**. Each one of the VGCEs **101** to **108** performs amplitude equalization over its respective optical path signal. Each one of the eight optical path signals from the first optical system then propagates to a respective one of the optical switches **121** to **128**.

Similarly, an input WDM optical signal from a second optical system is input at the input **2** of the programmable OADM **10** and propagates to the input optical amplifier **12** where it is amplified. The input WDM optical signal from the second optical system then propagates to the primary DSCM **22**. The primary DSCM **22** performs preliminary chromatic dispersion and slope of dispersion compensation over the input WDM optical signal from the second optical system. The input WDM optical signal from the second optical system then propagates to the DeMUX **32** where it is de-multiplexed into eight optical path signals from the second optical system such that each one of the eight optical path signals from the second optical system includes four channels. Each one of the eight optical path signals from the second optical system propagates to a respective one of the secondary DSCMs **91** to **98**. Each one of the secondary DSCMs **91** to **98** performs secondary chromatic dispersion and slope of dispersion compensation over its respective optical path

signal. Each one of the eight optical path signals from the second optical system then propagates to a respective one of the VGCEs **111** to **118**. Each one of the VGCEs **111** to **118** performs amplitude equalization over its respective optical path signal. Each one of the eight optical path signals from the second optical system then propagates to a respective one of the optical switches **121** to **128**.

Each one of the optical switches **121** to **128** is used to perform the add/drop function or establish through paths. In its "bar" state, any one of the optical switches **121** to **128** forms a through path and routes its respective optical path signals from the DeMUXs **31** and **32** to the MUXs **33** and **34**, respectively. In its "cross" state, any one of the optical switches **121** to **128** performs an add/drop function by routing its respective optical path signals from the DeMUXs **31** and **32** to the MUXs **34** and **33**, respectively.

Depending on the state of the optical switches **121** to **128**, some of the optical path signals from both the first and second optical systems are multiplexed, at the MUX **33**, into a first output WDM optical signal. The first output WDM optical signal is output at the output **133** of the MUX **33** and propagates to the output DSCM **23**. The output DSCM **23** performs output chromatic dispersion and slope of dispersion compensation over the first output WDM optical signal. The first output WDM optical signal then propagates to the output optical amplifier **13** where it is amplified and it is then output at the output **3** of the programmable OADM **10**.

Depending on the state of the optical switches **121** to **128**, some of the optical path signals from both the first and second optical systems are multiplexed, at the MUX **34**, into a second output WDM optical signal. The second output WDM optical

signal is output at the output **134** of the MUX **34** and propagates to the output DSCM **24**. The output DSCM **24** performs output chromatic dispersion and slope of dispersion compensation over the second output WDM optical signal. The second output WDM optical signal then propagates to the output optical amplifier **14** where it is amplified and it is then output at the output **4** of the programmable OADM **10**.

The programmable OADM **10** is not limited to cross-connection between two optical systems. In another embodiment of the invention, the programmable OADM **10** is a cross-connection of N optical systems. Furthermore, in some cases the N optical systems form parts of a single optical system. The cross-connection of N optical systems includes N OADM elements, which are similar to the OADM elements **500** and **600**, cross-connected by a number of NxN switches.

Amplitude Compensation

At outputs **3** and **4**, the first and second output WDM optical signals, respectively, require specific target values of power that are suitable for transmission requirements of a respective one of the first and second optical systems. The input amplifiers **11** and **12** amplify the input WDM optical signals from the first and second optical systems, respectively, such that both input WDM optical signals have a common value of power. Although the powers of the input WDM optical signals are equalized, due to wavelength dependent amplitude ripple, respective channels of the input WDM optical signals from the first and second optical system may have different powers. Equivalently, two optical path signals of the optical path signals from the first optical system may not have the same power. Similarly, two optical path signals of the optical path signals from the second optical system may not

have the same power. Consequently, the VGCEs **101** to **108** and VGCEs **111** to **118** perform amplitude equalization of the optical path signals from the first and second optical system, respectively, such that the optical path signals all have a common value of power. Each one of optical path signals from the first and second optical system is multiplexed through one of the MUXs **33** and **34** resulting in the first and second output WDM optical signals, respectively. The output amplifiers **13** and **14** amplify the first and second output WDM optical signals, respectively, such that the power of each one of the first and second output WDM optical signals is set to a target value which is suitable for transmission requirements of a respective one of the first and second optical systems.

In the preferred embodiment of Figure 1, all paths between a MUX/DeMUX pair have a VGCE connected between a DSCM and an optical switch (or equivalently, between a DeMUX and an optical switch). For example, the VGCE **101** is connected between the DSCM **81** and the optical switch **121** (or equivalently, between the DeMUX **31** and the optical switch **121**). In another embodiment of the invention one or more MUX/DeMUX pairs have one or more paths in which a VGCE is connected between an optical switch and a MUX. For example, in another embodiment of the invention, the VGCE **101** is connected between the optical switch **121** and the MUX **33**. In this other embodiment of the invention, the VGCE **101** provides a mute function for a respective one of the optical path signals from either the first or second optical system, depending on the state of the optical switch **121**.

Chromatic Dispersion and Slope of Dispersion Compensation

At outputs **3** and **4**, the first and second output WDM optical signals, respectively, are required to have specific

target values of chromatic dispersion and slope of dispersion that are suitable for transmission requirements of a respective one of the first and second optical systems. These requirements must be met irrespective of the state of the optical switches **121** to **128**. This is achieved by assuring that at the optical switches **121** to **128** the optical path signals from the first and second optical systems have a common chromatic dispersion and common slope of dispersion. The primary DSCMs **21** and **22** perform preliminary chromatic dispersion and slope of dispersion compensation over the input WDM optical signals from the first and second optical system, respectively, such that the input WDM optical signals from the first and second optical system have common values of chromatic dispersion and slope of dispersion. In the preferred embodiment of Figure 1, although the primary DSCMs **21** and **22** perform preliminary chromatic dispersion and slope of dispersion compensation, the values of chromatic dispersion and slope of dispersion of the optical path signals from the first optical system are only roughly equal to respective ones from the second optical system. Consequently, the secondary DSCMs **81** to **88** and the secondary DSCMs **91** to **98** are used to perform chromatic dispersion and slope of dispersion compensation over the optical path signals from the first and second optical system, respectively, such that the optical path signals from the first and second optical system have common values of chromatic dispersion and slope of dispersion. Each one of optical path signals from the first and second optical system is multiplexed through one of the MUXs **33** and **34** resulting in the first and second output WDM optical signals, respectively. The output DSCMs **23** and **24** perform output chromatic dispersion and slope of dispersion compensation over the first and second output WDM optical signals, respectively, such that each one of the first and second output WDM optical signals has values of chromatic

dispersion and slope of dispersion equal to a respective one of the target values of chromatic dispersion and slope of dispersion.

In a preferred embodiment of the invention, the primary DSCMs **21** and **22**, the secondary DSCMs **81** to **88** and **91** to **98** are chosen such that the common values of dispersion and slope of dispersion are equal to an average of the target values dispersion and slope of dispersion, respectively, of the first and second output WDM optical signals at outputs **3** and **4**, respectively. A common value for the chromatic dispersion or slope of dispersion which is equal to the average of the respective target values of chromatic dispersion or slope of dispersion, respectively, at outputs **3** and **4** is not essential and other respective common values are suitable.

In a preferred embodiment of the invention, the primary DSCMs **21** and **22** are broadband DSCMs performing preliminary chromatic dispersion and slope of dispersion compensation and the secondary DSCMs **81** to **88** and **91** to **98** are narrow-band DSCMs performing secondary chromatic dispersion and slope of dispersion compensation. In another embodiment of the invention, the accuracy of the primary DSCMs **21** and **22** and the output DSCMs **23** and **24** is high enough such that secondary chromatic dispersion and slope of dispersion compensation is not required. In this other embodiment of the invention the secondary DSCMs **81** to **88** and **91** to **98** are not present. In some cases required target values of chromatic dispersion and slope of dispersion at the output **3** are the same as target values of chromatic dispersion and slope of dispersion at the output **4**. In such cases the common values of chromatic dispersion and slope of dispersion are set to the required target values of chromatic dispersion and slope of dispersion, respectively, at the output **3** and the output **4** and there is no need for the

output DSCMs **23** and **24**. Consequently, in yet another embodiment of the invention the output DSCMs **23** and **24** are not present.

In another embodiment of the invention the optical path signals from the first and second optical systems are set to common values of chromatic dispersion and slope of dispersion in a single step by performing secondary chromatic dispersion and slope of dispersion only. In this other embodiment of the invention, the primary DSCMs **21** and **22** are not present and the secondary DSCMs **81** to **88** and **91** to **98** are broadband DSCMs.

In some instances slope of dispersion of the output signals at the outputs **3** and **4** is not crucial and only one of the two OADM elements **500** and **600** includes secondary DSCMs. For example, in another embodiment the secondary DSCMs **81** to **88** are not present. In this other embodiment, the secondary DSCMs **91** to **98** apply secondary chromatic dispersion and slope of dispersion compensation to a respective one of the optical path signals from the second optical system such that respective ones of the optical path signals from the first and second optical system have common values of chromatic dispersion and slope of dispersion which are specific to the respective ones of the optical path signals (or equivalently, specific to each one of the switches **121** to **128**).

In an embodiment that has N OADM elements cross-connected together, with at least N-1 OADM elements of the N OADM elements having secondary DSCMs, satisfied are chromatic dispersion requirements at outputs of the N OADM elements. In an embodiment that has N OADM elements cross-connected together, with all of the N OADM elements having secondary DSCMs, satisfied are both chromatic dispersion and slope of

dispersion requirements at outputs of the N OADM elements. In an embodiment that has N OADM elements cross-connected together each including an accurate input DSCM and an accurate output DSCM but no secondary DSCMs, satisfied are both chromatic dispersion and slope of dispersion requirements at outputs of the N OADM elements.

Multiplexing and Eliminating Effects of Cross-talk

In some embodiments of the invention dead-bands are introduced in the input WDM optical signals by limiting channel frequencies at which optical signals are produced by, for example, optical transmitters within the N optical systems. In one embodiment of the invention, the input WDM optical signals carry dead-bands and are de-multiplexed into eight optical path signals each having four channels as shown at **201, 202, 203, 204, 205, 206, 207** and **208** in Figure 2A. For example, at **201**, channels 1, 2, 3, and 4 are grouped into a one of the eight optical path signals while, at **202**, channels 5, 6, 7 and 8 are grouped into another one of the eight optical path signals. There are either two or four dead-bands between any two concurrent optical path signals as shown at **211, 212, 213, 214, 215, 216** and **217** in Figure 2A. Dead-bands are placed between concurrent optical path signals to mitigate filtering penalties in de-multiplexing the input WDM optical signals from the first and second optical systems and avoid cross-talk (or MPI) between the optical path signals due to a finite roll-off over a range of wavelengths. The number of required dead-bands placed between the concurrent optical path signals depends on the roll-off. A sharp roll-off which is achieved with more expensive MUXs and DeMUXs requires fewer dead-bands whereas a more gradual roll-off obtained from less expensive MUXs and DeMUXs requires a greater number of dead-bands to avoid cross-talk. In another embodiment of the invention, there are more

than four channels per optical path signal resulting in fewer optical components and an increased spectral efficiency when there is a need for dead-bands. In yet another embodiment of the invention, there are fewer than four channels per optical path signal resulting in more flexibility and a decreased penalty due to equalization.

Figure 2B shows an arrangement of another embodiment of the invention at **301** in which some concurrent optical path signals have no dead bands between them. Dead-bands at **311**, **312**, **313** and **314** exist between concurrent optical path signals at **301** and **302**, between concurrent optical path signals at **302** and **303**, between concurrent optical path signals at **308** and **309**, and between concurrent optical path signals at **309** and **310**, respectively. There are no dead-bands between concurrent optical path signals at **303** and **304**, between concurrent optical path signals at **304** and **305**, between concurrent optical path signals at **305** and **306**, between concurrent optical path signals at **306** and **307**, and between concurrent optical path signals at **307** and **308**. Embodiments of the invention are not limited to eight optical path signals per OADM element. In other embodiments the input WDM optical signals of the first and second optical systems are each de-multiplexed into a number of optical path signals. For example, as shown at **301** to **310**, in another embodiment of the invention the input WDM optical signals of the first and second optical systems are each multiplexed into ten optical path signals.

In another embodiment of the invention, the input WDM optical signals from the first and second optical systems are de-multiplexed into distinct groups with each group having a distinct number of channels to suit particular cross-connection requirements.

Eliminating Effects of Cross-talk

In a preferred embodiment of the invention, all paths beginning at any one of the DeMUXs **31, 32** and ending at any one of the MUXs **33, 34** have approximately the same optical path length. This is achieved by having the paths contain similar functional elements. For example, every path includes one of the DSCMs **81** to **88** and **91** to **98** and one of the VGCEs **101** to **108** and **111** to **118** and as such the paths have approximately equal optical path lengths. Since the paths have approximately equal optical path lengths, frequency leakage form one of the paths into other paths remains coherent and is re-combined constructively at a respective one of the MUXs **33, 34**. For example, frequency leakage, form a path containing the secondary DSCM **85**, into two path containing the secondary DSCMs **84, 86** results in two signals each carrying frequency leakage within a respective one of the two paths. The two signals and the path signal within the path containing the secondary DSCM **85** are coherent due to the approximately equal optical path lengths and are re-combined at least partially constructively at the DeMUX **33**. As a result, effects of coherent cross-talk (or MPI) are reduced and the integrity of the output WDM signal is maintained at the output **133**.

In some instances completely eliminating coherent cross-talk is not a crucial issue. Therefore, other embodiments of the invention have one or more express paths in which there are no secondary DSCMs, no VGCEs and no optical switches. For example, in another embodiment of the invention there are two express paths. A first express path is between one of a number of outputs of the DeMUX **31** and a respective input of the MUX **33**, and a second express path is between one of a number of outputs of the DeMUX **32** and a respective input of the MUX **34**. For example, in this other embodiment of the invention there

are no secondary DSCMs, **81** and **91**, no VGCEs **101** and **111** and no optical switch **121**. Fewer DSCMs, VGCEs and optical switches result in a decrease in complexity of the programmable OADM **10** at the expense of an increase in MPI.

Numerous modifications and variations of the present invention are possible in light of the above teachings. It is therefore to be understood that within the scope of the appended claims, the invention may be practiced otherwise than as specifically described herein.